FLORIDA KEYS CARRYING CAPACITY STUDY

ASSESSMENT OF NEARSHORE BENTHIC COMMUNITIES OF THE FLORIDA KEYS

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First Revision

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ABSTRACT

There is a consensus that many changes in coastal marine ecosystems worldwide are anthropogenically driven. It has been asserted that anthropogenic impacts are responsible for degradation of coastal marine ecosystems in the Florida Keys, however there is a paucity of data that support this conclusion. This project entails an investigation of nearshore (<1 km from shore) benthic communities of the Florida Keys. It was designed to identify spatial and temporal variations within nearshore benthic communities and their associated nutrient regimes and to determine if these variations may be associated with human land use activity in the Florida Keys. Working hypotheses included:

- H_1: Nearshore benthic communities and their associated nutrient regimes exhibit spatial/temporal variation throughout the Florida Keys.

- H_2: There is a significant relationship between human land use activity and spatial/temporal variation of nearshore benthic communities and their associated nutrient regimes throughout the Florida Keys.

The project began with the creation of maps of the current distribution and composition of nearshore benthic communities using intensive surveys and recent aerial photographs. Next, historic aerial photographs were used to construct a complete time series of maps at multiple sites within the study area. The nature of changes within nearshore benthic communities at those sites was investigated. Nutrient samples were also collected near the time series sites to characterize the nutrient regimes of nearshore benthic communities. Finally, all project data and available county-wide land use activity data were incorporated into a geographic information system (GIS) database. Database queries and spatial analyses were conducted to explore relationships between land use activities, nearshore nutrient regimes, and nearshore benthic communities in the Florida Keys. Eventually, the results of this project may be incorporated into the development of a model that predicts the effects of land use activity and anthropogenic nutrient enrichment on nearshore benthic communities of the Florida Keys.

1.0 INTRODUCTION

Humans tend to modify the environments they occupy. Coastal residents, ecosystem managers, and marine scientists have speculated that human land use activity, especially nutrient enrichment, may play an important role in the changes that occur in many coastal marine ecosystems. However, pathogens, large storms, climatic shifts, and geologic events also contribute to changes within these ecosystems, thus making it difficult to attribute causation to anthropogenic or natural disturbances (Short and Wyllie-Echeverria 1996). Despite dedicated research efforts, many basic questions remain unanswered. What is responsible for changes in coastal marine ecosystems? Which changes in coastal marine ecosystems are naturally induced, and which are the direct result of human activity? Are there any measures that may be taken to diminish anthropogenic impacts on coastal marine ecosystems? As public environmental awareness increases, there is a growing demand for answers to these questions.

1.1 NUTRIENT ENRICHMENT IN COASTAL MARINE ECOSYSTEMS

A great deal of contemporary research is focused on the effects of nutrient enrichment on coastal marine ecosystems (for reviews, see Bricker and Stevenson 1996, Paerl 1997). Nutrient enrichment can have dramatic effects on marine ecosystems; a multitude of examples for benthic communities have been well documented (Borum and Sand-Jensen 1996; Duarte 1995; Orth and Moore 1983; Short 1987; Valiela et al. 1997b). Although there are many natural sources of nutrients in marine ecosystems (e.g. atmospheric deposition, parent bedrock, nutrient recycling, oceanic import) the majority of research has been dedicated to exposing human land use activities (e.g. agriculture, sewage disposal, industrial practices, land development) as a source of nutrient enrichment. Many studies have implicated anthropogenic eutrophication as the major cause of decline in coastal marine ecosystems (Borum and Sand-Jensen 1996; Cornwall et al. 1996; Henriksen et al. 1997; Kreitler and Browning 1983; McClelland et al. 1997; Short and Burdick 1996; Smith et al. 1981; Tomasko et al. 1996; Tomasko and Lapointe 1991; Valiela 1992; Valiela et al. 1992).

Two locations on the Atlantic Coast of the United States, Chesapeake Bay and Waquoit Bay, have been investigated extensively with respect to nutrient enrichment and changes in coastal marine ecosystems (Boynton et al. 1996; Cornwall *et al*. 1996; Dennison et al. 1993; Fisher et al. 1992; Madden and Kemp 1996; McClelland and Valiela 1998a; McClelland and Valiela 1998b; McClelland *et al*. 1997; Neckles et al. 1993; Orth 1977; Orth and Moore 1983; Short and Burdick 1996; Staver and Brinsfield 1996; Stevenson et al. 1993; Valiela et al. 1997a; Valiela *et al*. 1992; Valiela *et al*. 1997b). At these two locations, researchers have cooperated in an attempt to characterize communities and trophic structures; investigate nutrient sources, eutrophication, and biogeochemical nutrient cycling; describe water quality, watersheds, aquifers, and groundwater transport; quantify land use activity; and model the effects of land use activity on coastal marine ecosystems. Despite these comprehensive investigations, it has proven difficult to define linkages between land use activity and changes in coastal marine ecosystems. A similar array of investigations have been conducted in the Florida Keys (Table 1), however, only a few investigations (Lapointe 1997; Lapointe and Clark 1992; Lapointe and Matzie 1996; Lapointe et al. 1990; Lapointe et al. 1994) have been focused specifically on the relationships between land use activity and coastal marine ecosystems.

1.2 COASTAL MARINE ECOSYSTEMS OF THE FLORIDA KEYS

The Florida Keys are a chain of more than 1700 islands extending for more than 300 kilometers in a southwesterly direction from the southern tip of Florida (Figure 1). The islands are generally small; they have a total area of 266 km^2, and a total of 2990 km of shoreline. The Florida Keys are bounded by Biscayne Bay on the northeast, the Atlantic Ocean on the east and south, the Gulf of Mexico to the west and north, and Florida Bay to the northwest. The Florida Keys National Marine Sanctuary (FKNMS), Everglades National Park, Dry Tortugas National Park, and Biscayne National Park are the four principal resource management areas that encompass the Florida Keys.

The coastal marine ecosystems of the Florida Keys comprise three dominant habitats: mangroves, seagrasses, and coral reefs. Mangroves are a dominant feature of the land-sea margin throughout the Florida Keys. Mangrove fringed islands and banks function as wildlife habitat as well as a key source of food. The mangrove prop roots provide substrate for a wide variety of marine organisms. Seagrasses are the principle component of benthic marine habitats in the Florida Keys; they occupy over 70% of the FKNMS (Fourqurean, *in press*). Seagrasses provide the critical primary production and nursery habitat needed to support commercial and recreational fisheries. The structure and distribution of seagrass communities varies throughout the Florida Keys; they form extensive meadows and patchy beds, and are also found scattered throughout other habitats (Figure 2). Coral reefs, patch reefs, and hardbottom habitats cover approximately 7%, 1% and 19% of the FKNMS, respectively (FMRI/NOAA 1998). Coral habitats exist in a general nearshore to offshore gradient of hardbottom, patch reef, coral reef (Figure 2). Corals also provide habitat for marine life, and are important to commercial fisheries and recreational industries.

The unifying geologic feature of the Florida Keys is Key Largo Limestone, a Pleistocene formation of lithified fossil coral, which extends as a solid mass from Miami to the Dry Tortugas. The keys may be divided geologically into two main sections: 1) the upper and middle keys, from Soldier Key to Newfound Harbor Keys, where the Key Largo Limestone is exposed and 2) the lower keys, Big Pine Key and beyond, where the Key Largo Limestone is overlain with another Pleistocene formation, Miami Oolite (Shinn 1988). Additional facies, including Holocene reefs, lime muds, and modern carbonate sands are found throughout the Florida Keys. The distribution of these geologic formations (Figure 3) contributes to variations in the distribution of marine habitats in the Florida Keys.

The hydrologic nature of the Florida Keys is also influenced by the distribution of these geologic formations. The permeability and porosity of limestone facilitates seepage of groundwater, and there is no aquifer structure, with the exception of a few small freshwater lenses located under some of the larger lower keys. Groundwater can move vertically and horizontally throughout the limestone, even back and forth between the Atlantic side and the Florida Bay side of the keys due to flushing and tidal pumping (Shinn et al. 1994). It appears that anthropogenic nutrients could not only enter nearshore surface waters via runoff or canals, but may plausibly be transported laterally to offshore subsurface waters through the carbonate substrate (Paul *et al*. 1997; Shinn *et al*. 1994). The presence of submarine seeps has indicated that groundwater may be transported to nearshore habitats. Groundwater discharge have been shown to be a mechanism of nutrient enrichment in the nearshore waters of the Florida Keys and eastern Florida Bay (Corbett *et al*. 1999) although the source of nutrients and the extent of enrichment has not yet been determined. Anecdotal evidence suggests that similar seeps may occur offshore where areas of exposed limestone come into contact with overlying waters. Thus, there is potential for natural or anthropogenic nutrient enrichment to reach both nearshore and offshore communities.

Excessive nutrient enrichment has been observed to disrupt marine ecosystems. The disruption can often result from community composition shifts, which cause changes in biogeochemical cycling (Valiela *et al*. 1997b). However, benthic communities are not always adversely affected by nutrient enrichment. It has been determined that in many places in the Florida Keys, biomass and productivity of benthic plants are nutrient limited (Fourqurean *et al*. 1995; Fourqurean *et al*. 1992a; Fourqurean *et al*. 1992b) and initially respond positively to nutrient enrichment. There is also evidence that suggests nutrient limitation (Figure 4), and consequently plant response to nutrient enrichment, may differ throughout the Florida Keys (Fourqurean, unpublished data). Studies have shown that there is more phosphorous available offshore, near the reef tract (Leichter et al. 1996; Szmant and Forrester 1996), while groundwater and Florida Bay water are relatively rich in available nitrogen (Fourqurean *et al*. 1993; Lapointe *et al*. 1990). It can be expected that the effects of nutrient enrichment may vary due to the different nutrient limitations and regimes of nearshore and offshore benthic communities.

1.3 RELEVANCE OF PROPOSED RESEARCH

Brian E. Lapointe and his colleagues have conducted some preliminary research that focused on the effects of anthropogenic nutrient inputs on coastal marine ecosystems in the Florida Keys. The basis for most of Lapointe's research in this area is the hypothesis that human wastewater is a significant source of enrichment to groundwaters in the Florida Keys. One of his earliest investigation of this nature, "Nutrient coupling between on-site sewage disposal systems, groundwaters, and nearshore surface waters of the Florida Keys" (Lapointe *et al*. 1990) attempts to confirm this hypothesis. This study concluded that this seasonal variation in groundwater transport, combined with seasonal variations in sewage input, accounts for observed increases in nearshore surface water nutrients during the summer. A later investigation, "Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys" (Lapointe and Clark 1992), attempted to extend the influence of these enriched groundwaters from the nearshore to offshore (>6 km from the shoreline) habitats. The conclusions drawn from this investigation are somewhat vague, but generally state that nearshore waters are reaching a critical state of eutrophication as indicated by "apparent ecological dysfunction" and change in coral communities. Another investigation, "Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters of the Florida Keys" (Lapointe and Matzie 1996), followed a similar line of reasoning, and concluded that the anthropogenic nutrients in groundwater are being transported offshore as a result of periodic rainfall events, and are contributing to the decline of coral reefs. Three additional studies (Lapointe 1997; Lapointe *et al*. 1994; Tomasko and Lapointe 1991) have focused on the observed effects of eutrophication on seagrass communities and the hypothesized effects of eutrophication on coral reefs. The results of these three studies were incorporated into the investigations described above.

Collectively these studies by Lapointe et al. indicate that anthropogenic nutrient enrichment of groundwater may be occurring locally in the Florida Keys and that nutrient enrichment can have an effect on benthic marine communities. However, the implied hypothesis, that anthropogenic nutrient enrichment affects coastal marine ecosystems of the Florida Keys, has never been subjected to rigorous testing by Lapointe et al. or any other investigators. This project addresses the implied hypothesis using an objective approach that allows for formal hypothesis testing and statistically supported conclusions.

1.4 COOPERATIVE RESEARCH

The project is part of specific studies conducted to develop the Florida Keys Carrying Capacity Study, an ambitious effort to evaluate the ability of the Florida Keys ecosystems to withstand all impacts of additional land development activities.

This project was designed to enhance the current Florida Keys National Marine Sanctuary (FKNMS) Water Quality Protection Plan (WQPP) monitoring program supported by the Environmental Protection Agency (EPA). The objectives of this monitoring program include: determination of the sources of pollution in the FKNMS, evaluation of pollution reduction and elimination efforts in the FKNMS, and evaluation of progress towards achieving and maintaining water quality standards, and evaluation of progress towards restoring and protecting the living marine resources of the FKNMS (Fourqurean et al. 1996). Data collected by EPA/WQPP monitoring efforts are providing a baseline for spatial and temporal variation of water quality, corals, and seagrasses in the FKNMS. Field sampling and data processing methods for this project was designed so that data will be compatible with the existing EPA/WQPP data.

The water quality monitoring consists of quarterly sampling of nutrient concentrations, biological parameters, and field parameters at 150 stations throughout the entire FKNMS (Figure 5). These FKNMS water quality data are coupled with data from Florida Bay, Biscayne Bay, Whitewater Bay, Ten Thousand Islands and the Florida Shelf (Jones and Boyer 1997). Together, these data characterize spatial and temporal variability of water quality within in the FKNMS. The biological resource monitoring is divided into two parts: corals and seagrasses. Coral reef monitoring is conducted at forty permanent stations throughout the eastern two thirds of the FKNMS (Figure 5). Coral cover, species richness, and community dynamics are determined through written and videographic data collection along permanent transects (Jaap *et al*. 1998). The seagrass monitoring is conducted at three levels at stratified random sites located throughout the entire FKNMS. Level I monitoring takes place quarterly at thirty permanent stations (Figure 5). Data collected at these permanent stations are used to assess seasonal trends in seagrass productivity, community composition, C:N:P relationships, and demographics. Level II monitoring is used to assess spatial and temporal variation in these same parameters. Level III monitoring estimates spatial and temporal variations in seagrass cover and abundance throughout the FKNMS (Fourqurean *et al*. 1996). Approximately 250 level II and III sites are sampled each summer in addition to the quarterly level I sites.

The distribution of EPA/WQPP sampling stations provide fair coverage of the majority of the FKNMS, however, nearshore habitats have not received much attention. This project extended existing water quality and biological resource monitoring into the nearshore areas. As described earlier, the shoreline is an important interface between the marine environment and the geologic structures of the keys; groundwater may serve as a common physical link between the two, providing a means of natural or anthropogenic nutrient enrichment. A thorough investigation of variations in nearshore nutrient regime and benthic communities may provide insight into the possible impacts of human land use activity on coastal marine ecosystems of the Florida Keys.

1.5 JUSTIFICATION OF PROJECT DESIGN

This project was designed with two goals in mind: 1) to produce data which will enhance the existing EPA/WQPP data sets, and 2) to produce quantitative data which may be used in the statistical testing of this project's hypotheses. The first goal was accomplished by adoption of the EPA/WQPP sampling methods and protocols, whenever possible. Achievement of the second goal, however, proved to be a bit more demanding. The following section outlines how the organization, experimental design, and statistical methods selected for this project were influenced by the concepts of hierarchy theory, landscape heterogeneity, and autocorrelation.

A landscape may be conceptually organized into a hierarchical structure with separate functional ecosystem components whose processes occur within defined levels characterized by specific spatial and temporal scales (O'Neill et al. 1986). The components of one level interact with each other at that level, but may also generate behaviors and constraints for components at higher levels. In the context of an ecological investigation, a reference level contains an observed event or pattern, with its explanation found in the level below, and its significance reflected in the level above (Urban et al. 1987). In order to determine the significance of an observed variation within a landscape, investigators must follow a three-step procedure: 1) determine the scale or level at which the observed variation occurs, 2) identify the mechanisms that cause the variation, and 3) relate the variation to behaviors at other levels. This procedure functioned as a foundation for this project.

First, the investigation focused on detection of spatial and temporal variations in distribution or composition of nearshore benthic communities and their associated nutrient regimes. Then, the spatial and temporal scales of any observed variations were determined, and attempts were made to identify the mechanisms responsible for producing the variations. The potential mechanisms included natural or anthropogenic disturbance, abiotic constraints (hydrology, meteorology, geology), biotic interactions (competition, demographics), and more complicated processes, such as biogeochemical cycling. Finally, the significance of the variations and mechanisms were explored in the context of the entire coastal marine ecosystem of the Florida Keys.

The concept of landscape heterogeneity also had a tremendous influence on the development of this project. Landscapes are inherently heterogeneous; they consist of a mosaic of patches formed by a wide variety of disturbances, abiotic conditions, and biotic interactions (Forman and Godron 1986). Landscape heterogeneity is often the result of underlying structures or processes that preclude random spatial or temporal distribution of the components of a landscape. Although heterogeneity may interfere with observations or experiments, often it is of primary interest to an investigation (Dutilleul and Legendre 1993). In the case of this project, landscape heterogeneity was the focus of the investigation; sampling efforts were directed towards the detection and quantification of variations that existed in nearshore benthic communities.

Investigations conducted within a heterogeneous landscape must address the issue of scale in the experimental design. Many studies in ecology are conducted at a small scale, usually less than 10 meters (Simmons et al. 1992). However, in order to detect patterns or variability on the larger scale of a landscape, an experimental design must employ an appropriate scale, lag, and sample size (Carlile et al. 1989). The scale depends on the hierarchical level of the observations, and may range from an individual, to a community, or even an entire landscape. The scale of an investigation determines the size of the sample unit. The lag of an investigation is a distance associated with independence of sampling units; sample units farther apart than the lag are considered to exist under different conditions. The scale, lag, and sample size for observations in this project were determined using methods similar to those described by Carlile et al. (1989). Variations were then observed using methods determined to be appropriate for the hierarchical level or scale of each observation. Determining the spatial and temporal scales at which variations occur in a landscape can be accomplished using a variety of procedures. Investigators have successfully used a combination of procedures to detect multiple patterns within landscapes, with spatial scales ranging from 10 to 600 meters (O'Neill et al. 1991). Methods similar to those used by O'Neill et al. (1991) were used throughout this project to detect variations (e.g. habitat patchiness, localized nutrient gradients, large scale abiotic processes) in the nearshore benthic marine landscape of the Florida Keys.

Finally, the concept of autocorrelation must be recognized as an important influence on the development of this project. Ecological investigations have often revealed that for observations separated in space or time the values at one point are influenced by the values at neighboring points. This general property is referred to as autocorrelation. Values may be positively autocorrelated (more similar than expected) or negatively autocorrelated (less similar than expected); values may be spatially or temporally autocorrelated. Unfortunately, autocorrelated data violates the assumption of independence required by most statistical tests. Therefore many investigators are interested in proving that there is no autocorrelation, so that they may proceed with standard statistical hypothesis testing. Alternatively, they may want to prove that autocorrelation is present, quantify the amount of autocorrelation, and make use of that property in the development of models (Legendre 1993). This alternative course of action was taken with autocorrelated data collected throughout this project. Several methods were used to calculate the degree of autocorrelation within a spatial data set. In general, correlograms, variograms, or periodograms were used for point data, and Geary and Moran indices were used for areal, or polygonal, data.

2.0 METHODS

2.1 STUDY AREA

Investigations were concentrated in four areas of the Florida Keys: Key Largo, Marathon, Big Pine, and Key West (Figure 6). Sampling sites were located in a nearshore zone (<1 km from the shoreline) in each of these four areas. The nearshore zone was selected as the study area for several reasons. Although the study area for the EPA/WQPP project includes the entire FKNMS, very little nearshore sampling is conducted (Fourqurean *et al*. 1999; Jaap *et al*. 1998; Jones and Boyer 1997). The data collected in this project extended the current monitoring coverage all the way into the shoreline. Also, it has been suggested that if nutrients are being transported offshore via groundwater, the nearshore zone is one area where the flux may be detectable (Corbett *et al*. 1999; Shinn *et al*. 1994). It was necessary to limit the investigation to four areas of Florida Keys due to resource constraints. The four areas were selected because they include expanses of heavily developed urban areas adjacent to sparsely developed coastal ecosystems. The distribution of study sites within these four areas provided excellent representations of nearshore benthic communities and nutrient regimes throughout the Florida Keys.

2.2 NEARSHORE BENTHIC COMMUNITIES

Intensive surveys documented the distribution, composition, and condition of current nearshore benthic communities of the Florida Keys. Sites were selected using a stratified random method, hexagonal tessellation. This assured reasonably uniform coverage while adhering to the random distribution requirements for statistical testing. At each site physical measurements and community composition data were collected. Physical measurements included differential global positioning system (DGPS) coordinates, water condition parameters (conductivity, temperature, dissolved oxygen, turbidity), and sediment/substrate description. Community composition was assessed using the Braun Blanquet quadrat method (Table 2) (Braun-Blanquet 1972) adopted by the EPA/WQPP seagrass monitoring project (Fourqurean *et al*. 1996). The percent coverage of benthic taxa (Table 3) was recorded from ten 0.25 m^2 quadrats haphazardly located within 10 m of the DGPS coordinates. Community composition data was collected at approximately 1500 sites, with an estimated sampling density of 6 sites per km^2 (Figures 7a-d). The community composition data were used to create nearshore benthic community classifications and describe spatial variation in nearshore benthic communities.

There is a wide range of approaches to generating a classification of species composition. Individual species may be analyzed, or species may be lumped into functional groups (e.g., seagrass, red algae, stony coral). Either species or functional groups may be censused as simply present at a site, or quantitatively as counts of individuals, estimates of areal coverage (density), or frequency of occurrence in quadrats. Compositional dissimilarity may emphasize low-density species (e.g., Jaccard dissimilarity on presence/absence data), emphasize the few highest species (e.g., Euclidean or Manhattan distance), or something in between (e.g., Bray-Curtis dissimilarity). Samples may be merged into clusters based on their similarity to the most similar member of that group, the least similar, or an average or group centroid. A classification may be hierarchical for convenience, even though there is no theoretical or empirical basis for ecological communities originating by bifurcations. These different approaches emphasize different aspects of the ecology, and thus produce classifications that are more informative for different uses.

To the extent that the observed species compositions fall into a small set of discrete types, all approaches will identify those groups and produce essentially the same classification. To the extent that the observed species compositions vary more continuously, either along gradients, with intermediate or mixed composition, or with many idiosyncratic species, the different approaches will partition the variation quite differently. For a general classification not directed to a single specific goal, our approach was to identify those groupings of sites or classes that are identified by a consensus of the approaches. We computed dissimilarities between all pairs of samples based on presence/absence and Jaccard dissimilarity, counts of individuals with Bray-Curtis and Manhattan distance, and logarithmically-spaced cover classes and Bray-Curtis and Manhattan distance. These five dissimilarities were computed from both species data and functional groups. Average-linkage, complete-linkage, and Ward's clustering were applied to each of the 10 dissimilarity matrices to produce hierarchical clusterings. For each of the 30 clusterings, the hierarchical tree was inspected, and from 5 to 9 groups were defined. Finally, these 30 classifications were compared to identify sets of samples that were consistently placed together within a class.

The community classification results served as groundtruthing and verification data for a map of the current distribution of nearshore benthic communities of the Florida Keys. The map was created from the most recent (1997) FDOT black and white aerial photographs of the Florida Keys shoreline. The photographs were selected to include all land and all nearshore benthic communities included in the four study areas (Table 4). The photographs were digitized and imported into the GIS database. Community composition data collected earlier at groundtruthing sites were used to assist in the supervised classification of the benthic communities present in the images. Following the classification and groundtruthing procedures, additional community composition data were used to verify the GIS map: the classification of a site on the map was compared with the actual community type that was present at that site in the field. Since classification data is nominal, the comparison method consisted of 1) calculation of cross tabulations between the classified map and the map containing verification data and 2) calculation of kappa coefficients of agreement and chi square values (Table 5) (Bonham-Carter 1994). These were used as a measure of accuracy of the completed map.

2.3 TIME SERIES MAPPING

An assessment of constancy and change in nearshore benthic communities of the Florida Keys was conducted by creating time series maps from historic aerial photographs (Figure 8). The shoreline at potential mapping sites was classified by site location and adjacent land use activity. Four classes, bayside sparsely developed (BS), bayside heavily developed (BH), oceanside sparsely developed (OS), and oceanside heavily developed (OH) were delineated using data from the Monroe county land use activity (e.g. land use classification, population density and septic tank or injection well density) database. In each of the four study areas, two sites were selected from each of the four classes (Figures 9a-d). The 32 sites each comprise a 1 km^2 block directly adjoining a 1 km stretch of shoreline with one continuous land use classification. At each of the sites, a complete set of historic aerial photographs was used to construct a time series of benthic community maps. The Florida Department of Transportation (FDOT) has taken detailed black and white photographs of the Florida Keys shoreline every 3 or 4 years since the 1950s; a complete time series included four decades of photographs. Only sites that had complete photographic records were considered for this part of the investigation. The photographs (Table 6) were digitized, georectified, and assembled in a time series format using ArcView.

At each of the 32 sites, thirty points were randomly selected for time series analyses. A 10 m radius buffer was drawn around each point, and the amount of benthic macrophytes within each buffer was recorded for each time step (Figure 10). The amount of benthic macrophytes were recorded as combinations of cover (bare, sparse, moderate, and dense) and shape (partial, whole). Examples of these combinations include: dense partial (DP), moderate whole (MW). If the combination remained the same from one year to the next, a score of zero was assigned for that time step. Every increase in either cover or shape (such as sparse to moderate, or partial to whole) was assigned a score of +1, and every decrease (such as dense to moderate or whole to partial) was assigned a score of -1 (Table 7). The net change for each point was calculated by adding the scores for each time step at that point. The variability for each point was calculated by taking the standard deviation of the scores for each time step. The mean temporal change and mean temporal variability for each site were calculated by taking the average of the net change and standard deviation for all thirty points at that site.

2.4 NEARSHORE NUTRIENT REGIME

Sampling of nearshore nutrients was used to describe the current nutrient regime associated with the nearshore benthic communities of the Florida Keys. A permanent nearshore to offshore nutrient transect was located near each of the time series study sites (Figures 11a-d). Each of the 32 transects consisted of a single line of four sites perpendicular to the shoreline. The transect sites were selected using a stratified random method: the transect was divided into four segments (0m to 100m, 100m to 250m, 250 to 500m, and 500 m to 1km); one site was selected from each segment. The data collected at these transects was used to determine the nature of nearshore to offshore nutrient gradients.

At each nutrient transect site the following data were collected: physical measurements, benthic community composition, plant samples, epiphyte samples, and sediment samples. Physical measurements and community composition would be recorded using the methods previously described. Samples of the seagrass *Thalassia testudinum*, a dominant plant species found throughout the study area, were collected, placed in ziploc bags, and stored on ice. As soon as possible, the epiphytes were scraped from the seagrass leaves and frozen. Morphometric measurements were taken from the seagrass leaves. In the laboratory the seagrass samples were dried, weighed, and analyzed for nutrient content (C:N:P). The epiphytes samples were dried, weighed, and analyzed for chlorophyll a. Two surface sediment cores were taken using 10 cc syringes. The upper 2 cc of each core were transferred to scintillation vials and frozen. In the laboratory, sediment samples were analyzed for porosity, chlorophyll a, organic content, and C:N:P.

A N:P ratio of 30:1 for the seagrass *T. testudinum* indicates a balance in the availability of N and P. Deviations from this ratio can be used to infer whether N or P availability is limiting growth (Fourqurean and Zieman in press). Inferences may also be made regarding the potential effects of increased nutrient availability due to human activites.

2.5 SPATIAL ANALYSES

Geographic information system (GIS) technology was used extensively throughout this project. Documentation of benthic communities in coastal marine ecosystems is an excellent application of GIS technology, and has already played a crucial role in several investigations of this nature (Ferguson and Korfmacher 1997; Janauer 1997; Lehmann and Lachavanne 1997; Muller 1997; Mumby et al. 1997; Narumalani et al. 1997; Norris et al. 1997; Robbins 1997; Ward et al. 1997). A GIS can be used to assimilate diverse forms of data into a functional database consisting of separate data layers. Examples of data layers include: bathymetry, benthic community distribution, water turbidity, substrate type, plant C:N:P ratios, and land masses. All data collected throughout this investigation was incorporated into a new database. GIS software was used to query the database for patterns, conduct spatial analyses, and help determine the significance of relationships between data layers. The GIS was also used to present spatial and temporal relationships between nearshore benthic communities and human land use activities in a visually meaningful way to the public, scientific colleagues, and resource managers.

Field data was collected at random points throughout the study area, yet the data collected at these points represent continuous fields. Continuous surfaces or areas representing these discrete data points can be calculated using non-interpolative or interpolative methods, as summarized by Bonham-Carter (1994). Non-interpolative methods involve the assignment of a point value to an entire polygon, using criteria such as grids, zones of influence or Thiessen polygons. Interpolative methods, namely contouring or surface modeling, involve triangulation, distance weighting, and kriging. In triangulation, data points are connected to form a mosaic of Delaunay triangles; the surface passes each data point, and the value of each triangle is only determined by the value of three data points. However, the distance between three data points can have a great effect on the size of the triangles; the zones of influence of data points may vary across the surface. Distance weighting methods calculate surface values based upon weighted moving averages within specified zones of influence. The most common method, inverse distance weighting, gives data points close to the interpolation point more influence on the interpolated value than data points far away from the interpolation point. Weighting methods produces surfaces that usually do not include the data points. Kriging uses an equation to produce a separate weighting parameter for each interpretation point, taking spatial covariances into effect. Of the three interpolative methods, kriging is the most versatile in terms of describing autocorrelative (signal) and residual variation (noise) (Bonham-Carter 1994). For this reason, kriging was used to calculate surfaces in this project. Once data was converted into the proper format for spatial data analysis, a process known as map modeling (Bonham-Carter 1994) was used to explore spatial and temporal relationships. These maps assisted in the inductive processes of visualization of spatial and temporal relationships and formation of hypotheses.

The GIS was used to investigate possible relationships between nearshore benthic communities and land use activities of the Florida Keys. FLUCCS land use data, along with nearshore benthic community data, time series data, and nearshore nutrient data, were incorporated into the GIS database. The ArcView Spatial Analyst extension was used to explore relationships between land use and: 1) the distribution of nearshore benthic communities, 2) changes in nearshore benthic communities, and 3) nearshore nutrient regimes. Simple modeling operations between pairs of data layers were used to produce an integrated data layer to be used in multiple layer comparisons. Relationships which appeared significant in the initial GIS data explorations were subjected to spatial analyses.. The land use data used in the spatial analyses were based on FLUCCS polygons and classifications. Two separate analyses were performed; for both analyses, the land use classes were condensed into two classes (undeveloped and developed, also referred to as slightly developed and heavily developed) as listed in Table 8.

Our first approach builds on the concept that any offshore biotic response (densities of taxa or taxa groups, and nutrient parameters) to onshore land use should weaken with distance offshore. Therefore, we applied a general linear model sequentially fitting effects of distance to shoreline, categorical land use at the nearest point of land, and an interaction between distance offshore and nearest land use (Figure 12). Under this model, a significant interaction term with sign opposite that of the land use main effect has the potential to reflect an impact of land use. An elaboration of this approach includes the effects of sediment type (mud to coarse sand) and sediment depth. Sediment type and depth have extremely strong associations and presumptively causal effects on species composition. If benthic substrate is taken to be relatively fixed and unaffected by land use, then partialling out the effect of substrate on biotic responses corrects for the non-causal correlation between development onshore and benthic substrate offshore. Conversely, benthic substrate may be the mechanistic pathway for some forms of land use impacts, so partialling out the effect of substrate may eliminate true causal impacts of onshore land use.

Our second approach builds on the concept that many potential stressors such as nutrients from septic tanks disperse through groundwater. Therefore, another metric for the potential degree of land use impact is the amount of developed land within a given radius of the offshore sample (Figure 13). Because the intent is to assess the impact of land use and not just the amount of land nearby (correlated with distance offshore), we again take a stepwise approach, removing a potential effect of land area within the radius first, and then interpreting an effect of the percent of that land that was developed. Percent developed is used rather than amount developed in order to be approximately independent of the prior land area factor. This metric may be more reasonable for the Big Pine Key study area, where many sites are in channels with land on both sides. Because we have even less reason to expect linear responses to area and percent area, we test for this effect with Spearman partial rank correlations.

3.0 RESULTS

3.1 NEARSHORE BENTHIC COMMUNITIES

The consensus classification of community composition data collected at nearly 1,400 sites throughout the Florida Keys study area includes eight classes. Four of the eight classes are dominated by seagrasses; one class is a community of mixed macrophytes, and the remaining three classes are hardbottom communities (Table 9). Out of the 1,367 sites included in the classification analyses, 1,329 sites fell into one of the eight classes; 38 sites were not assigned to a class (Figure 14). A little over half of the sites were classified as seagrass community, while approximately one third were classified as hardbottom community. The percentage of sites belonging to each class varied among study areas (Table 10), with a significant decrease in seagrass communities and increase in hardbottom communities moving southwest from Key Largo out to Key West (Figure 15). The distribution of the nearshore benthic community classes throughout the four study areas is shown in Figures 16 a-d. All nearshore benthic community data was subjected to further spatial analyses; those results are included in the spatial analysis results below.

3.2 TIME SERIES MAPPING

Time series analyses of the black and white DOT aerial photographs reveals very little change in the distribution of nearshore benthic communities in the Florida Keys since 1959 (Figure 17). There are no significant differences in the amount of keys-wide benthic macrophyte cover with respect to time (1959-1997, six time steps), location (oceanside or bayside), or land use (heavily or slightly developed). However, there are clear differences in the magnitude and direction of the minimal changes detected with respect to study area. The mean temporal change at most Key Largo and Marathon sites were positive, reflecting small net increases, while the mean temporal change at most Big Pine and Key West sites were negative, reflecting slight net decreases. The mean temporal variability was significantly higher in Key Largo and Marathon, indicating a greater number of points in those study areas were changing through time. The mean temporal variability was significantly lower in Big Pine and Key West, indicating more stability at sites in those study areas (Figures 18a-b). No time series data was subjected to further spatial analyses, since there were no significant relationships between mean temporal change or mean temporal variability and land use.

3.3 NEARSHORE NUTRIENT REGIME

Preliminary analyses of *Thalassia testudinum*, sediment, and epiphyte samples collected at 32 transects did not reveal any significant keys-wide trends in nutrient parameters with respect to location (oceanside or bayside), distance from shore (50 m, 100 m, 250 m, or 500 m), or land use (heavily or slightly developed). However, ArcView plots of nutrient data revealed potential significant relationships may exist within study areas (Figures 19a-d). All nutrient data (Table 11) were therefore included for further spatial analyses; those results are included in the spatial analysis results below.

3.4 SPATIAL ANALYSES

All nearshore benthic community data and nearshore nutrient regime data were subjected to further spatial analyses. The results of these analyses are complex, and relationships between project data and land use should not be generalized for the entire Florida Keys. Both analytical approaches reveal significant relationships between nearshore benthic community data, nearshore nutrient data and land use within a given study area, but these relationships rarely hold true for all study areas. The results of the first approach, the general linear model, are included in Appendix 1a (taxa groups) and Appendix 1b (individual taxa). Note that for each response variable, the first line provides the coefficients and significance for the stepwise effects of distance offshore (Offshore), land use status of the nearest land (Development), and the interaction between distance offshore and land use status. The second line provides the same information for a sequential model with sediment type, sediment depth, distance offshore, land use status of nearest land, and the interaction between distance offshore and land use status. The results for the second approach, the radial model, are included in Appendix 2a (taxa groups) and Appendix 2b (individual taxa). For both sets of tables, it is important to remember that individual taxa results cannot be interpreted as tests for significant impacts on each taxa. In addition, with 83 separate tests in each table, roughly 4 tests should be significant at the $p<.05$ level just due to chance. However, given the moderate statistical power of using such crude land use classes, table-wise corrections for multiple comparisons would insure that even a very large response would not be deemed significant. The intended, valid interpretation of the individual taxa tables is as a screen for potential indicator species. If monitoring for changes over time in benthic species is contemplated, these screens suggest candidate species.

In light of these results, a question remains: does the available data provide evidence for any impact or potential impact of Florida Keys land use on nearshore benthic community composition or nutrient regimes? The available FLUCCS land use data offer crude categories of land use, and allow analysis of potential impacts at an intermediate spatial scale. The land use polygons are on the orders of 100s to 1000s of meters, and this project's sampling points are on the scale of 100s of meters apart and within 1 kilometer of the shoreline. Therefore, analyses of relationships between variation in benthic community composition and land use has little power to detect impacts at spatial scales on the order of 10s of meters (small impacts, such as canals or outfalls), nor can it detect impacts that range over spatial scales greater than a few kilometers (notably, any land use impact that is strong or diffuse enough to affect all of the Florida Keys).

4.0 CONCLUSION

This project was designed to identify spatial and temporal variations within nearshore benthic communities and their associated nutrient regimes and to determine if these variations may be associated with human land use activity in the Florida Keys. The first working hypothesis, that nearshore benthic communities and their associated nutrient regimes exhibit spatial or temporal variation throughout the Florida Keys, has been conclusively addressed. We have determined that both nearshore benthic communities and their associated nutrient regimes do exhibit spatial variation throughout the Florida Keys. However, nearshore benthic communities were found to exhibit very little temporal variation through the past 40 years, even in the face of tremendous land development in the Florida Keys. The second working hypothesis, that there is a significant relationship between human land use activity and spatial or temporal variation of nearshore benthic communities and their associated nutrient regimes throughout the Florida Keys, merits further investigation. Results indicate that substrate, not land use, is the most important factor associated with benthic community composition. Two modeling approaches have identified potential relationships between a few individual taxa, taxa groups, nutrient parameters, and land use, but very few of these relationships are significant throughout the Florida Keys.

We recommend that this project's modeling efforts should be continued, but with a more accurate, ideally quantitative land use data set. This would enable researchers to fully realize the potential of the enormous nearshore benthic community database generated by this project. In addition, we feel that a more comprehensive nearshore nutrient sampling program should be initiated in the Florida Keys. Systematic, detailed sampling in the canals would provide researchers with a solid foundation on which to address questions of possible nearshore eutrophication in the Florida Keys.

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